

Review

Health Monitoring and Safety Evaluation of the Offshore Wind Turbine Structure: A Review and **Discussion of Future Development**

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Abstract: With the depletion of fossil energy, offshore wind power has become an irreplaceable energy source for most countries in the world. In recent years, offshore wind power generation has presented the gradual development trend of larger capacity, taller towers, and longer blades. The more flexible towers and blades have led to the structural operational safety of the offshore wind turbine (OWT) receiving increasing worldwide attention. From this perspective, health monitoring systems and operational safety evaluation techniques of the offshore wind turbine structure, including the monitoring system category, data acquisition and transmission, feature information extraction and identification, safety evaluation and reliability analysis, and the intelligent operation and maintenance, were systematically investigated and summarized in this paper. Furthermore, a review of the current status, advantages, disadvantages, and the future development trend of existing systems and techniques was also carried out. Particularly, the offshore wind power industry will continue to develop into deep ocean areas in the next 30 years in China. Practical and reliable health monitoring systems and safety evaluation techniques are increasingly critical for offshore wind farms. Simultaneously, they have great significance for strengthening operation management, making efficient decisions, and reducing failure risks, and are also the key link in ensuring safe energy compositions and achieving energy development targets in China. The aims of this article are to inform more scholars and experts about the status of the health monitoring and safety evaluation of the offshore wind turbine structure, and to contribute toward improving the efficiency of the corresponding systems and techniques.

Keywords: offshore wind turbine; health monitoring system; feature information extraction; reliability analysis; safety evaluation

1. Introduction

Considering the problems of the continuous shortage of international fossil energy and environmental pollution, many countries have increased their development of clean renewable energy. Offshore wind energy has attracted worldwide attention because it has many advantages, including huge energy reserves, continuous resource stability, short construction period, and mild environmental influence. As of the end of 2017, the new installed capacity of the global wind power was 52.57 GW, and the cumulative installed capacity has reached 539.58 GW with a year-on-year growth of 10.85% [1]. Simultaneously, the new installed and cumulative capacity of offshore wind power are



4.33 GW and 18.81 GW, respectively. It is estimated that the percentage of the global electricity supply generated from the wind power will be up to 8%–12% by 2020 [2]. The potential installed capacity of the offshore wind energy in China is about 500 GW, which is 23 times as much as the capacity of the Three Gorges Projects [3]. Compared with the onshore wind power, the offshore wind energy in China has the obvious advantages of high wind speed, high output, and a long lifetime. Hence, it has become the important component of the national energy sustainable development strategy in recent years. In 2017, the cumulative installed capacity of the offshore wind power in China reached 2.79 GW with the new installed capacity of 1.16 GW, as described in Figure 1, and the cumulative capacity surpasses Denmark's position to be placed among the top three in the world. As shown in Figure 2, seven provinces in China have begun to develop offshore wind power in 2017 and it is predicted that the cumulative installed capacity of the offshore wind power in 2017 and it is predicted that the cumulative installed capacity of the offshore wind power in China will reach 5 GW by the end of 2020, which has a very large potential for development and utilization.



Figure 1. Development of the offshore wind power in China and worldwide (inset).



Figure 2. Distribution of installed capacity of offshore wind farms built and under construction in 2017.

With the development of wind energy technology, the offshore wind power industry has shown a trend toward larger capacity, taller towers, and longer blades in recent years, such as the exemplified by the Pinghaiwan offshore wind farm in China (capacity of 5 MW, blade length of 64.0 m, and tower height of 90.0 m) [4], the Westermost Rough offshore wind farm in the United Kingdom (capacity of 6 MW, blade length of 77.0 m, and tower height of 102.0 m) [5], and the Gode offshore wind farm in Germany [5] (capacity of 6 MW, blade length of 77.0 m, and tower height of 77.0 m, and tower height of 110.0 m). Hence, an important issue which comes with this change is the structural safety of the wind turbine under operational conditions, because the tower and blades have become more flexible. In particular, more than 700 project accidents have occurred in the last five years [6,7], and the structural operational safety of the offshore wind turbine (OWT) should be given more extensive attention.

The events leading to failure of the OWT usually happen in the blades, tower, and foundation, and are varied [8,9]. On one hand, the accidents could be induced by complex external excitations [10]. For example, Ishihara reported that the wind turbines on Miyakojima Island were extensively damaged due to the excessive bending moment of towers induced by the typhoon Maemi in 2003 [11]. A similar incident happened on 16 September 2013, and one coastal wind farm was catastrophically destroyed because of the direct influence of the super typhoon Usagi. Specifically speaking, the strong wind excitations induced strains in the blades and the tower exceeded the failure threshold strains of the structural materials, which led to the blade fracture and tower collapse [12]. Furthermore, in 2015, the typhoon Soudelor, with the maximum instantaneous wind speed of more than 59.5 m/s, struck Taiwan, and it was found that the blades of one wind turbine were fractured and six towers of turbines had snapped [13]. On the other hand, the fatigue operation and structural faults originating from insufficient supervision will also lead to the damage to wind turbine structures [14,15]. In 2008, the typhoon Jangmi collapsed the wind turbine structures which were located in Taichung Harbor of Taiwan and snapped the lower tower into two parts. After a study investigation and lab experiments, insufficient bolt strength and poor bolt quality control during construction were considered as the likely causes of the tower's collapse [16]. Simultaneously, the three main reasons of insufficient material strength, the resonance effect, and human error were identified for the blade damage in the same incident [17]. Since the OWTs are usually located in areas which are far from land, the workers cannot regularly perform onsite inspections of the structure. Therefore, real-time health monitoring and accurate operational safety evaluation should be carried out on the OWT structure. This gradually becomes the key point for the safety monitoring and the operation management of the offshore wind farm.

In recent years, health monitoring systems and safety evaluation techniques of the OWT have obtained more attention from researchers and engineers. Some reviews have been completed to provide owners and managers of wind farms with useful summaries and advice in order to reduce structural failure risks and economic losses. One part of these reviews is related to the summary of the development trend [18] and the future challenges [19] of wind turbine condition monitoring. The other parts mainly focus on the health monitoring systems and techniques of the wind turbine, including gearbox [20], blades [21,22], and the tower [23]. A discussion on the data processing, feature extraction, operational evaluation techniques, and the health monitoring system was presented for the first time in Ref. [24]. However, the discussion is not comprehensive or sufficient in explaining the applicability of the mentioned methods for OWTs. In this paper, the health monitoring systems and safety evaluation techniques of the OWT structure, including monitoring system categories, data acquisition and transmission, feature information extraction and safety evaluation, and the intelligent operation and maintenance will be systematically investigated and summarized. This is done with the intention of determining how to construct reasonable systems, utilize the measured data, assess the structural safety, and achieve intelligent maintenance during the process of the health monitoring and safety evaluation of the OWT in order to better manage and operate the offshore wind farm.

This paper consists of seven sections: In Section 2, the health monitoring systems of the OWT are first summarized. Subsequently, techniques of data acquisition and transmission, feature information

extraction and identification, safety evaluation and reliability analysis, and intelligent operation and maintenance in the offshore wind farm are comprehensively reviewed in Sections 3–6, respectively, mainly based on the practical engineering applications. In Sections 7 and 8, the future development trend of health monitoring systems and safety evaluation techniques of the OWT are further discussed and principal conclusions are explained.

2. Health Monitoring System

2.1. SCADA and CMSs

Since offshore wind farms are always far away from the mainland, many remote health monitoring systems have been applied in order to reduce failure risks, identify fault occurrences, and improve the working performance by analyzing the data measured from the wind turbine. Supervisory control and data acquisition (SCADA) systems and condition monitoring systems (CMSs) are considered as the two most common means of structural health monitoring. SCADA systems, with more than 20 variants, are widely approved and deployed to the offshore wind power industry. They are usually used to monitor several parameters related to different wind turbine components (e.g., structural vibration levels, temperature, bearings, tower, and drive train acceleration). In addition, SCADA systems are also utilized to obtain different factors as inputs of the wind turbine (e.g., wind speed, wind deviations, and wind direction angle) or outputs (e.g., rotor speed, blade angle, output active, and reactive power) [25]. The measured signals, recorded at a low sampling frequency (usually at 10 min intervals and smaller than 0.002 Hz), can be processed in a timely manner by many data analysis tools to detect the fault location and degree, explain problem causes, and automatically provide the operators and managers with real-time online feedback and useful suggestions [26]. Simultaneously, the researchers, on one hand, make full use of the data collected by the SCADA systems for further analysis of the parameter identification, fault diagnosis, and risk prediction [27]. On the other hand, the traditional SCADA system and monitoring data are also combined with new analysis and process techniques to perfect and update the system so that they can show a more efficient and reliable performance. Schlechtingen studied a new adaptive neuro-fuzzy inference system model to obtain different monitoring signals and achieve automatic diagnosis and prediction based on the SCADA system [28,29]. Hereafter, a new generalized model was presented for wind turbine anomaly identification. The research introduces a new index, defined to quantify the abnormal level of the wind turbine condition, and a fuzzy synthetic evaluation method, used to integrate the identification result into the traditional SCADA system [30]. In addition to system and model improvements, the utilization of many new methods has also been attempted in the SCADA system. For this purpose, Yang proposed an alternative condition monitoring technique based on investigating the correlations among the relevant SCADA data, and completed the health condition quantitative assessment of one turbine under varying operational conditions [31]. Furthermore, a Bayesian framework was introduced to explore the feasibility and potential of identifying abnormal turbine states based on the SCADA data [32]. These studies and techniques provide new directions for the improvement and updating of SCADA systems.

CMSs are considered as another important tool to monitor and measure data such as the vibration, load, wind speed, and temperature of the OWT structure continuously at a higher frequency (usually more than 50 Hz) in order to examine whether the wind turbine is operating correctly [33]. When a fault or damage has been detected based on an alarm signal from the CMS, a diagnosis system, which obtains data at a sampling frequency greater than 10 kHz, could be activated to determine the degree and location of the potential fault either automatically or artificially. This kind of system can usually be implemented for the operators, indicating the health condition, obtaining the reliable alarm, and taking essential actions on the OWT by many analysis techniques including vibration analysis, motor current signature analysis, operational modal analysis, and the acoustic emission technique [23,34,35]. For example, the ADAPT wind system designed by GE Energy Company can

monitor 150 static variables on the bearing, gearbox, and generator, and achieve the aims of detecting the gear tooth damage and fault diagnostic and reporting the alarm based on the time and frequency domain analysis. A new system called CMSWind, which is being invented by the CMSWind project and is still in the development phase, combines the operational modal analysis and the acoustic emission technique to monitor rotary components [33].

Nowadays, most CMSs were attempted to be integrated into the SCADA systems, because CMSs can only focus on the vibration data explanation and are still not standardized, in contrast to the SCADA system [36]. It is a good phenomenon that CMSs can either collect data from the SCADA system or allow its results to be integrated into the SCADA display [23]. The integration between CMS and SCADA systems has occurred in the condition-based maintenance (CBM) System, InSight intelligent diagnostic system (IDS), and wind turbine in-service system (WTIS) and is beneficial in directly considering any other signals or variables of the entire controller network [33]. Furthermore, as CMS and SCADA systems continue to merge, they will eventually produce one comprehensive system able to significantly improve the efficiency and accuracy of the structural health monitoring of the OWT. The general layout of structural health and condition monitoring systems for OWTs can be described as in Figure 3 [33,37].





2.2. Health Monitoring System of Blades

As we all know, the blades, which always consist of different composite materials with complex geometry and sections, are considered as the most flexible components and are easily damaged by environmental excitations of the OWT structure. When the damage of blades occurs, it may accumulate and reflect as cracks and delamination, which will lead to rotor imbalance, aerodynamic asymmetry, and even blade fracture [38]. Hence, the health monitoring of blades has an important significance on the structural safety of the OWT. As early as 1994, Sutherland used the two nondestructive testing techniques of acoustic emission (AE) and coherent optical (CO) to monitor the behavior of a typical wind turbine blade and detect the damage during static experiments [39]. Afterwards, a new structural neural system was invented and developed for the structural health monitoring (SHM) of large blades at the National Renewable Energy Laboratory [40]. This system can also be implemented in a

quasi-static proof test to track failures based on the AE monitoring technology. In 2013, Song studied a piezoceramic-based wireless sensor network (WSN) and tried to complete the health monitoring of wind turbine blades with an active sensing approach [41]. The damage of blades was detected and evaluated during a static loading test and a wind tunnel experiment. However, static experiments are not sufficient to construct a monitoring system and still pose difficulties in achieving the blade monitoring because the blades rotate periodically under the operational conditions.

The acoustic emission (AE) is the acoustic waves generated by a composite material when it undergoes deformation and rupture [39]. Furthermore, the AE technique can be implemented through recording and analyzing acoustic signals in order to determine AE sources and the corresponding location of damage in the materials. AE has proven its high effectiveness in detecting and identifying damage in wind turbine blades. Blanch and Dutton successfully achieved the AE monitoring field experiment of an operating Windharvester wind turbine based on a real-time radio telemetry system. The research results indicated the damage location and the corresponding propagation process in the blades [42]. A remote health monitoring project of the blades of an operating NEG-MICON NM48/750 wind turbine, which successfully acquired data under operational conditions for more than six months, has also been completed based on the AE technique [43]. This system can be connected to the SCADA system of the OWT and has a good performance regarding the fast integration, data exchange, and modular processing to external systems. In addition, another AE monitoring system of blades was designed considering cyclical fatigue loads and possibly will be applied for the offshore wind farm in the future [44].

When the blades of the OWT experience deformation and damage, the corresponding structural strain, which is directly related to the stresses and loads applied to the material, will change at the same time [21]. Hence, many studies have implemented prototype systems for measuring strain online in operational wind turbines to track and detect damage. A health monitoring system for the blades of a SMART Wind Turbine Rotor project, consisting of accelerometer sensors, fiber optic temperature sensors, and fiber optic strain sensors, was invented by Sandia National Laboratory [45]. It operated for more than five months and measured deference data for the future optimization of the control system. Then, a fibrous Bragg grating (FBG) sensor began to obtain more attention because it is insensitive to electromagnetic interference and lightning. The FBG also has a better fatigue life and a longer-term stability than traditional strain gauges [46]. A FS2500 system and rotor monitoring system (RMS) were both used to measure the strain data and edgewise and flapwise bending moment data in order to access the blade damage performance, mass and aerodynamic imbalance, blade bending moments, and lightning strikes [33]. Schroeder et al. successfully installed a fibrous Bragg grating sensor system in a horizontal-axis wind turbine to achieve continuous online monitoring of the bending loads of blades for more than two years. The measured strain data can be used to evaluate the safety condition of blades and determine the fatigue loads for the whole turbine [47]. An integrated SHM system for blades of the floating OWT has been constructed using FBGs to develop an optical fiber-based data transmission module and to connect sensor nodes to a grid covering the whole blade [48]. This system will be further expanded to the whole structure (e.g., nacelle, tower, and blades) and applied in the actual offshore wind farm in the future.

Apart from the above systems, the IGUS ITS GmbH Company in Germany designed the BLADE control system, which utilizes accelerometer producers bonded directly to the blades and rotor to measure dynamic data and transfer wirelessly to the nacelle. The operational condition and the safety evaluation of blades of the wind turbine can be achieved by comparing spectra with those stored for common conditions [33]. Ozbek et al. monitored a 2.5 MW wind turbine according to three measurement systems based on the techniques of the strain gauges, photogrammetry, and laser interferometry, respectively. Then, the modal information of blades was identified for several standstill and operational conditions with different wind speeds [49]. In addition, a continuous line laser thermography system was presented for damage visualization of the wind turbine blades under operational conditions. The properties of the fully noncontact mechanism, data acquisition without

spatial scanning, and intuitive data interpretation make the proposed system suitable to monitor and detect the condition of long blades in the offshore wind farm [50]. Another thermography technique called infrared thermography detects variations in the thermodynamic properties of blades. Based on the temperature differences, it can further identify the flaws in the adhesive by showing a series of pictures [22]. X-ray imaging detection depends on quantitative information about density variations with the change of composite material properties or the internal delamination. It has a limited capacity for delamination detection compared with the thermography technique, which always takes the advantage of the perpendicularity of wave propagation with respect to the delamination and obtains higher detection sensitivity [51].

2.3. Health Monitoring System of the Tower and Foundation

The support structure of the OWT consisting of the steel tower and foundation is always designed to make sure that the wind turbines can safely generate power at a specific height. The instability and structural failure of the tower and the foundation, possibly induced by the extreme environmental excitations, fatigue loads, and natural disasters, may bring destructive results to the whole OWT. Therefore, it is necessary to achieve the structural health monitoring and develop the safety evaluation system for the tower and foundation of the offshore wind farm.

Due to the later development of offshore wind power, more research on the health monitoring systems of onshore wind turbines has been carried out. Firstly, the SCADA system is still effective for vibration acceleration monitoring on the top of the wind turbine tower located near the nacelle and tower connection [52]. However, the data measured from the SCADA system is insensitive to the dynamic analysis and parameter feedback on the tower structure because of the low sampling frequency of 0.1 Hz, or even lower frequencies [53]. In order to overcome this problem, the wireless sensor networks were applied in the health monitoring system of wind turbine towers. The dynamic data of vibrational acceleration and strain gauges can be collected at the different sampling frequencies of 50, 100, and 150 Hz and transmitted within the tower so that the modal analysis of the towers will be completed offline [54]. Furthermore, the supervised event server health monitoring system (SESHMS) was also presented and is considered as a relatively economical system based on the wireless sensor networks. The system consists of a certain number of Sun SPOTs (Sun Small Programmable Object Technology), which operates on Java-embedded software and contains an internal accelerometer, to obtain data and transmit the signals to the neighboring testing node. Then, the complete data was eventually transmitted to the base station using GSM (global system for mobile communication) in order to achieve the health monitoring and structural evaluation [55]. In addition, Smarsly et al. studied a decentralized remote system using the digital subscriber line (DSL) connection technique to record the dynamic data of displacement, acceleration, temperature, and wind speed during the same time period for further monitoring tasks, such as damage detection and lifetime estimation of the tower and foundation [56–58].

Recently, the smart wireless sensor networks have also been used for an integral SHM system of the OWT, consisting of three modules for damage detection, model validation, and evaluation, to determine the existence, location, and severity of the structural damage of the tower [59]. It has been demonstrated that the new system has a better performance in data acquisition quality and transition stability. Then, the online force identification, sensor fault identification, and damage detection of one 5 MW OWT was implemented based on an integrated SHM system, which was proposed to analyze the measured data online through the internet and provide the operator with the health state information of wind turbine towers [60]. As is well known, the tower and foundation always show the dynamic behaviors together because they are closely connected to each other. Hence, many systems involving synchronously monitoring the tower and foundation have begun to appear and be applied for the OWTs [61]. Devriendt et al. discussed a monitoring system which receives the data with a time-stamp from an timeserver in order to correlate them with the SCADA and Meteo data and be used for the long-term measurement of an OWT in the Belgian North Sea. It used the online scope-function to

monitor and send data to the onshore server using a dedicated fiber every 10 min [62]. These discussed systems aim to determine the integrity of the tower and foundation of the wind turbine, as shown in Figure 4.

The different foundation forms of OWTs, which mainly include monopole, gravity, tripod, jacket, suction bucket and floating techniques [63,64], require the adaptable health monitoring system. Wang et al. designed an online monitoring system for the Vestas 3 MW wind turbine with a bucket foundation to access the structural condition and obtain the modal information [63]. Then, an SHM system based on FBG sensors dedicated to an OWT model supported by a tripod foundation was presented. It has a good development potential in detecting and localizing the damage based on four damage indexes due to the better accuracy and can be used for OWTs with tripod foundations [65]. The Offshore Wind Infrastructure Lab (OWI-lab) has constructed an SHM system using excitation, acceleration, and displacement sensors to perform monopole foundation monitoring in the Belwind offshore wind farm. The researchers focused on the influence on the resonance frequencies and modal shapes with the operational and environmental variability and tried to determine any structural change potentially being concealed [66,67]. Also at the Belwind and NorthWind windfarms in the North Sea, the continuous monitoring of dynamic vibration acceleration and corrosion monitoring of the corrosion rates, corrosion potential, and oxygen concentration inside the monopole have been implemented during two years. Furthermore, the monitoring of stress and use of response estimation techniques at unmeasured locations by combining a limited set of response measurements enables the life assessment of foundation to be conducted [68].



Figure 4. Health monitoring systems of wind turbines [55,58,59,62]. SESHMS: server health monitoring system; WSN: wireless sensor network; DSL: digital subscriber line; DAS: data acquisition system.

3. Data Acquisition and Transmission

Generally speaking, the SCADA and CMS systems of OWTs have independent data acquisition and transmission modules to collect the structural dynamic behaviors and operational parameters, store signals in a central database, and then send the data to the onshore control center of the wind farm based on the available remote communication network. In the existing monitoring systems, the data acquisition tasks should be completed by different kinds of sensors, including displacement transducers, accelerometers, strain gauges, thermometers, and anemometers, at designed sampling frequencies and adaptable software based on many techniques, such as acoustic measurement, monitoring of power quality, and temperature and vibration analysis [26,33,69]. Besides, the laser interferometry [70], photogrammetry [49,71], and thermography [22,50] technologies are also applied at the wind farm, especially for blades with composite materials, to obtain information for condition detection and damage identification. These advanced methods are further hoped to be used at the tower and foundation, although the long-term monitoring tasks cannot be implemented at present. Prior to the specific analysis of the measured information from OWTs, the storage, management [72], pre-processing [73], and mining [74] of a large amount of data will be achieved in the specified database. It is helpful to delete the redundant information, improving the efficiency of analysis and guaranteeing the accuracy of conclusions. A novel structural health monitoring system which processes the high volume and high veracity of data sources in an integrated way was applied at the offshore wind farm in the Belgian North Sea [75]. The OWI-lab developed a big wind intelligence data platform with an integrated relational database and big data No-SQL (Not Only Structured Query Language) architecture in order to overcome the problem of the traditional data approaches being poorly suited to handle measured information over a long time period and with different sampling frequencies, scattered location, and a variety of data files.

Nowadays, the available remote communication network of offshore wind farms is comprised of and is implemented mainly based on fiber-optics laid in submarine cables which are connected to the offshore or onshore substations [76]. The transmission systems can continuously send the acquisition data from SCADA and other systems installed in OWTs to the onshore control center using the dedicated fiber which runs over the seabed [77]. However, the higher requirements of transmitting larger amounts of real-time dynamic monitoring data at high frequency have been proposed to achieve online structural modal identification and safety evaluation of OWTs in the future. The WSN technology has also started to receive recognition [78] and has been considered as a key method to develop the data acquisition and transmission systems for structural health monitoring [79,80].

The monitoring system generally consists of the data acquisition network and data distribution network, which includes storage and transmission modules mainly using wireless, GPRS (General Packet Radio Service), Bluetooth, a cellular network, code division multiple access (CMDA), and GSM, and is usually controlled by the management center [81]. Two transmission methods of acquired data within the turbine have been discussed. On one hand, the signals at all observed points may directly collect to the base station; on the other hand, the measured information of each node may be transmitted to the neighboring testing node until the complete data is obtained and is then sent to the operators [55]. At the wind farm, each wind turbine represents a single wireless network which transmits the measured data to the remote monitoring center by GPRS module in order to achieve full wireless communication by an optimized routing algorithm [37]. However, the increasing distance between the offshore wind farm and control center, growing data capacity, and more complex operational environments may bring more challenges to structural health monitoring based on WSN techniques. Hence, the capacity and reliability of data transmission needs to improve.

The DSL and broadband communication techniques have also attracted more attention in the data transmission of structural monitoring systems in recent years, especially for wind farms [58,61,82]. However, the DSL technique still needs to rely on the physical connection to achieve the information transmission task between the data acquisition system and the centralized control center. For the offshore wind farm, its efficiency may not have obvious advantages compared with the optical fiber transmission. In addition, the broadband transmission technique also faces the same problem as the WSN and requires higher data transmission abilities with the development of the offshore wind power industry.

4. Feature Information Extraction and Identification

The implementation of health monitoring systems of the OWT always serves for the structural safety evaluation, which depends on the techniques of feature information extraction and identification including modal identification, damage detection, and fatigue life assessment. The varieties of feature information and the occurrence of damage can be obtained and used to find the difference between the current and normal operational conditions in order to determine and evaluate the structural health. In addition, fatigue analysis can be implemented to determine the service life of OWTs and avoid unhealthy operation.

4.1. Modal Information Identification

The modal identification allows the extraction of the structural modal parameters such as modal frequencies, damping ratios, and mode shapes [83], only based on the measured response data induced by the unknown environmental or operational excitations. As is well known, the modal information identified based on vibration signals including the displacement, acceleration, and strain [84] under operational conditions not only reflect the dynamic characteristics of the structural vibration, but also are of great significance to the structural safety evaluation. The modal analysis techniques, including NExT(Natural Excitation Technique), ITD(Ibrahim Time Domain Technique), SSTD (Single Station Time Domain), ERA (Eigensystem Realization Algorithm), and SSI (Stochastic Subspace Identification), are important means to effectively master the operational behaviors and modal parameters for the large dams, long bridges, and many tall buildings, especially for the OWT because of the extremely difficult task in measuring excitations. However, the rotating blades dramatically change the characteristics of aerodynamic excitations and set limitations, which mainly include time variance and harmonic interference, on the applicability of operational modal analysis (OMA) to OWTs [85].

Due to the special arrangement of the rotating equipment of the OWT, the structure is excited by the combination of random excitations, which come from the ocean environment, and the harmonic inputs resulting from the unbalanced mass of rotating components or fluctuating forces under the operational conditions at the high rotating speed. Simultaneously, both natural and harmonic modal information induced by the two above excitations will be found in the structural vibrations. Especially when the tower height and impeller diameter increase, the difference between the rotating frequencies and the structural natural frequencies of the wind turbine structure becomes much smaller. The harmonic components may occupy most of the energy in structural vibration responses under the high rotating speed conditions. Finally, it will become harder to obtain the structural modal information by the classic analysis methods, because the vibration of natural modes may be completely submerged in the harmonic frequency band because of its low energy.

The most critical step to accurately obtain real structural modes is how to handle the strong influence of harmonic components mixed in measured data in the operational modal analysis of an OWT. To overcome this problem, Brincker firstly presented the concept of harmonic modes, which were considered as the modes consisting of the harmonic components with higher vibration energy in the responses resulting from the stable harmonic excitations during the process of operational modal identification [86]. The subsequent research proposed an indicator to distinguish the real structural modal information from harmonic modes, which were later considered as the false modes, with the modal frequencies being the same as the harmonic excitation frequencies and zero damping ratios, in output-only modal experiments based on the probability density function (PDF) method. Afterward, aiming at dealing with the harmonic interference on the operational modal analysis, many researchers tried to filter out the harmonic components ahead of the modal identification so that the measured vibration data would only contain the real structural modal information [87]. However, useful components may easily be lost without choosing a suitable filter because of the closer distance between the natural and harmonic modal frequencies. The differences in statistical properties between structural and harmonic signals, such as kurtosis and the PDF, have also been analyzed and utilized to distinguish the actual structural modes from the unknown harmonic modes by using the frequency

domain decomposition (FDD) method, singular value decomposition (SVD) method, and random decrement technique (RDT). Nevertheless, when the structural information is completely submerged in the harmonic components, the actual modal parameters cannot be obtained properly and the results will lead to unavoidable deficiency [88–91]. In addition, Pintelon proposed two algorithms, which are respectively based on the single-output signal and multi-output signals for suppressing and removing the harmonic influence with unknown varying frequencies in the continuous-time operational modal analysis [92,93]. However, good results could only be obtained when the distinction between the structural modal and harmonic frequency was clear. Additionally, differentiating the actual structural and harmonic modes has been achieved successively by using the new theory of transmissibility function [94,95], Hilbert–Huang transformation [96], and optimized spectral kurtosis [97], but then the ability of these methods to extract the modal information under strong harmonic disturbances needs to be further studied. Mohanty [98–100] had modified several classic modal identification methods, including the ITD, ERA, and SSTD method, to obtain the actual modal information considering the influence originating from the harmonics on the characteristic matrix of the structural system. However, it also has a limitation in engineering applications because the defect of the algorithm itself and its poor noise resistance may lead to unstable identification results.

In an actual project of the offshore wind power, the original related study on the operational modal identification for one 100 kW OWT in Demark was completed by using the NExT method and both the real modes and harmonic modes were identified based on the authenticity of the modes depending on the zero-value property of harmonic modes [101,102]. However, one can also find that the first modal frequency has been affected by the 1P harmonic due to the smaller frequency difference. Thereafter, Hansen utilized the SSI method to obtain the operational modal frequencies and damping ratios successively based on measured strain data with no coincidences between the harmonic frequencies and the actual modal frequencies [103]. Furthermore, to overcome the limitations of the periodically time-variant nature and the presence of harmonic components, a linear system identification methodology based on the Mathieu oscillator [104] and a Blind Source Separation and Independent Component Analysis (BSS/ICA) method [105] were also proposed to eliminate the interference resulted from rotating blades during the OMA process of the OWT. Similarly, the modal identification of both the blades and tower has been completed by Tcherniak based on the data measured in the wind turbine structure [106]. Additionally, a new modal identification method called the harmonic modified stochastic subspace identification (HM-SSI) method was proposed on the basis of Mohanty's ideas, which introduced the strong harmonic interference information obtained from measurement data into the traditional SSI method to possess stronger anti-noise capabilities and better recognition stability. Subsequently, this new method was used to successfully achieve the operational modal identification and safety evaluation of the OWT structure [107]. The modified SSI technique considering harmonic influence was also used to achieve the rapid structural health assessment of the wind turbine structure by analyzing the relationship between identified modal frequencies and harmonics [108].

Apart from the operational modal analysis under the operational conditions with strong harmonic influence, studies have also been implemented under standstill conditions or operational conditions at a low rotating speed in order to avoid the harmonic influence and accurately identify the real modal information of wind turbines. For example, the natural frequency and modal damping of the OWT supported by the monopole foundation were first identified by Damgaard for different Danish wind farms based on a thorough investigation of "rotor-stop" experiments for more than five years [109]. Then, the enhanced frequency domain decomposition (EFDD) method was applied to a 3.6 MW OWT's responses under ambient excitation for the estimation of the damping in normal operation with low wind speed [110]. Bajrić recently proposed an automated procedure based on the real vibration measurements and covariance-driven stochastic subspace identification (COV-SSI) method to identify the modal damping ratios of an OWT under nonoperating conditions [111]. In addition, Hu combined the poly-reference least Squares complex frequency domain (p-LSCF) method with a

data-driven stochastic subspace identification (DATA-SSI) approach and focused on the resonance phenomenon and environmental and operational influences on structural dynamic properties under normal operational conditions of a wind turbine system for a 5 MW wind turbine, on the basis of dynamic signals acquired continuously from the tubular tower over a period of two years [112,113]. It can be obviously found that the harmonic components in the vibration responses did not affect the natural modal information, because the identified modal frequencies at 0.41 Hz are far from the maximum 1P harmonic frequency at 0.25 Hz at the rotating speed of 15 rpm. The similar conclusion was also proposed by Häckell, comparing the first eigenfrequency at 0.33 Hz with the harmonic frequency at 0.25 Hz [114]. It is illustrated that the measured OWTs were designed to increase the structural modal frequency or reduce the rotating speed in order to widen the frequency interval between structure and excitations. In recent years, the OWI-lab also made more contributions to the structural operational modal analysis of OWTs. They tried to construct a complete set of monitoring systems and perfect the automated operational modal analysis method based on the measured data of wind turbines in the Belgian North Sea [115–117]. Simultaneously, the comparative studies using different techniques aimed at identifying the modal parameters were presented and the potential benefit of the continued health monitoring and operational modal analysis campaign was discussed [118–120].

4.2. Structural Damage Detection

Considering the long-term and possible unhealthy operation of the OWT under environmental excitations, structural damage may happen to many components, including the blades and tower. If the early damage is ignored or allowed to continue to develop and no timely repair action is taken, the failure risk may occur and lead to the structural collapse. Currently, the most extensive attention on damage detection and structural safety has been given to the blades and tower of the OWT. This is because that, on one hand, they are the most important components and comprise more than 40% of the total cost; on the other hand, they are also the most flexible and vulnerable parts because of the length, size, and material properties of blades and the height of the tower, often exceeding 80 m. In addition, the numerous connections of the tower are exposed to a corrosion environment and very sensitive to the external excitations. Therefore, the damage detection techniques have been rapidly developed and widely applied in the structural safety evaluation of wind turbines in recent years.

The fundamentals of damage detection depend on the changes in local mass, stiffness, and structural modal properties including modal frequencies, damping ratios, mode shapes, and other derived dynamic properties between the healthy and damaged states and will also be reflected in many corresponding indexes, such as the ASL, RMSD [121], WP [122], and VIB [122]. Hence, the structural damage can be identified, located, and even evaluated to a certain extent based on the measurement of changes in these properties and calculation with the above indexes [123]. The most common method of structural damage detection is considered as modal analysis or a model-based method, because the modal parameters have a direct relationship with the structural physical properties, which will change when the damage occurs. Furthermore, the variation that happens in the physical properties will lead to the detectable change in the modal properties, which can be used as a criterion to locate the damage [124]. One structural health monitoring approach of a wind turbine was implemented and the relationship between the natural modal frequencies and the stiffness reduction at the root of the blade was also discussed by using modal analysis based on acceleration data. The modal deflections and modal assurance criterion (MAC) were both used to determine the damage, and the damage feature may be extracted to provide the ability to both locate and quantify the reduction in stiffness in the blade root [125]. Considering the geometric nonlinearity, a new approach was proposed to calculate the modal strain energy (MSE) index in the nonlinear modeling of a generic 5-MW NREL blade and discuss the effect of damage length, location, and severity and also the effect of rotational speed and load amplitude. The result, being that the mode shape curvature and MSE indices have enough sensitivity to structural damage, was certified [126]. Simultaneously, a modern damage detection method based on wavelet transform has been presented to detect damage in the blades of large wind

turbines during normal operational conditions. This research is expected to provide a novel way to determine the damage location for the OWT structure [127]. Wang proposed a damage detection and diagnosis method for wind turbine blades based on dynamics analysis and mode shape difference curvature information [128]. It also provides a low-cost and efficient, nondestructive tool for wind turbine blade condition monitoring.

In addition to combination with modal analysis methods, the structural strain field data also plays an important role in detecting the damage existing in the wind turbine structure, including the blades and tower, because the slight change of structural physical properties may lead to the redistribution of structural strain. Generally speaking, the strain difference between adjacent strain sensors can be considered as an index of the presence of a crack and used as a feasible strategy to achieve remote fatigue damage detection for OWT towers. However, the success mainly depends on the reasonable arrangement of strain sensors around the tower and the prediction of extreme wind conditions [129]. To compare the capabilities of various strain sensors including fiber Bragg gratings (FBG), optical backscatter reflectometer (OBR), and normal strain gauges in damage detection, a pattern recognition technique using hierarchical nonlinear principal component analysis (h-NLPCA) based on the strain field measurement was described to detect damage during the certification test of the blades [130]. Based on the experimental results, the FBGs have more advantages over the strain gauges. FBGs are suitable for being embedded into the composite materials directly during the operational process of OWTs and monitoring more internal changes in strain, which strain gauges bonded onto the surface cannot achieve. In addition, the FBGs have a longer life in service health monitoring and damage detection systems based on strain measurements for offshore wind farms. Thereafter, Downey studied a hybrid dense sensor network consisting of thin-film sensors and FBGs and proposed a data-driven damage detection and localization method for wind turbine blades. This technique utilizes the error between the estimated strain maps and measures strains to define damage detection features and applies a novel method for inspecting large numbers of sensors without the need for complex model-driven approaches by fusing sensor data into a single damage detection feature [131].

The existence of damage, which comes from cracks, fractures, deformation, dislocation movement, delamination, and other reasons [132], will result in the redistribution of structural strain and have an obvious effect on the wave propagation and reflection on the structural surface or inside the structure. Hence, the difference of wave properties between normal and damage status can be obtained and applied in crack detection. Acoustic emission (AE) is the most popular technique of structural damage detection, especially for the wind turbine blades consisting of composite materials. The static and fatigue experiments of wind turbine blades were implemented and demonstrated the possibility of detecting the source of damage events and evaluating the condition of fiber composite blades using an AE monitoring system [133]. It can also be used to find out how the blade fails and how the failures propagate through the series of tests exposed to a large flapwise load [134]. Furthermore, many researchers have studied AE combined with advanced methods such as the passive structural neural system (SNS) [135] and thermoelastic stress measurement [136] and achieved the tests by using additional sensors including piezoceramic (PZT) patches, accelerometers, and strain gauges in order to improve the abilities in detecting both small cracks and damage [137–139]. Simultaneously, the comparative study results show that AE has better capability in detecting very small damages and is suitable to locate the spatial position and size of evolving damages [140]. Another nondestructive testing (NDT) technique for the wind turbine structure based on wave propagation and reflection is ultrasound. The main principle can be described as such: the ultrasonic pulse is sent into the blades or tower by an ultrasonic transducer and reflected at the back wall or at flaws within the material, which is recorded by the same sensors. The defect will be detected based on the data information about the thickness of the inspected structure obtained by the ultrasonic waves [141]. Furthermore, it has been shown that the ultrasonic technique may be used with imaging methods aimed at directly detecting and observing the structural damage and its change. A portable long-distance ultrasonic propagation imaging (LUPI) system has been studied by using anomalous wave propagation imaging

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(AWPI) methods and was verified to be possible to apply at the wind farms [142]. Then, a similar study presented a laser ultrasonic imaging and damage detection technique which can create images of ultrasonic waves propagating on the rotating structure and thus identify damage [143]. However, it has limitations regarding the inspection region, which needs a large number of wired sensors to be installed and the difficult field measurement on rotating objects using the noncontact laser interferometer.

For the OWTs under operational conditions, the conventional nondestructive testing and defect identification techniques cannot fully meet the requirement of structural damage detection because the rotating blades pose more difficulties to the field measurement and structural health assessment. However, the development of thermography, photogrammetry, and other imaging methods will help to successfully achieve the operational damage detection at offshore wind farms. The thermal imaging method is a subsurface defect or anomaly detection method, owing to temperature differences observed on the investigated surface, such as the wind turbine blade, during monitoring by using infrared sensors or cameras. The temperature difference is related to the change of thermal diffusivity and hence indicates material irregularity or damage [144]. The thermal imaging techniques on line laser thermography [50], infrared thermography, and pulsed thermography [145] were applied to complete the tasks on damage inspection and defect localization of blades, respectively. Thermography offers significant advantages over the NDT because of its fast, wide-area inspection capabilities and fully noncontact mechanism. Photogrammetry is a new measurement technique which is used to obtain 3D coordinates or displacements of an object based on the 2D images taken from different locations and orientations [146]. This method will be called videogrammetry when the sequences of pictures are used to monitor and collect the structural dynamic responses [71]. Photogrammetry can be efficiently applied in different research fields, such as full-field vibration monitoring, shape information extraction [147], structural deformation measurement [148,149], and blade inspection [150,151]. Combined with the digital image correlation (DIC) method, the field measurement of the deformation and strain of the blades was performed and the fault location and discontinuity were also identified. It reflects a great potential of the optical measurement technique and its potential for use in the wind industry for large-area inspection [152]. X-ray imaging [51] and laser Doppler vibrometry (LDV) [153] are both effective methods for measuring the internal structural change and responses in order to detect the damage. The former is sensitive enough to detect the change of at least 1–2% of the material thickness or density and can locate the internal inhomogeneities within the depth of the material [154].

As a basis of the NDT techniques, research on damage diagnosis algorithms and damage prediction methods have been completed to achieve the fast and accurate detection tasks on the wind turbine structure. An auto-associative neural network (AANN) and a novel approach to auto-association with radial basis functions (RBFs) networks were both used to propose the new algorithms [155]. The effectiveness of such pattern recognition methods was also verified based on the measured vibration data. In order to accurately predict the danger when the turbine will reach a damaged state, a damage prediction system for wind turbines based on a wireless sensor and actuator network was studied and was expected to take timely actions and protect the turbine operation from accidents [156]. These results may realize in damage detection and safety evaluation at offshore wind farms in the future.

4.3. Fatigue Life Assessment

Due to the complex ocean environment, the OWT is always subject to various cyclic excitations, such as those from wind, waves, currents, and rotor operation, which may pose risks of damage, failure, and fatigue to the structures. In order to avoid structural failure risk and determine the service time, studies on fatigue assessment have been widely implemented recently. First, the consideration of fatigue analysis can be denoted as the measurement and calculation of long-term fatigue loads acting on OWT structures. Generally speaking, it is still difficult for researchers and engineers to directly elucidate the excitations resulting from the environment and rotor operation, especially under extreme and fatigue conditions. A test system based on the Labview platform and control area network (CAN)

was proposed to achieve data automatic acquisition, stable transmission, and real-time monitoring for fatigue loads and fatigue lifetime prediction of wind turbine blades [157]. It was indicated that the system has satisfactory accuracy, good adaptation, and great practicality for the load measurement and fatigue life estimation of a large wind turbine. However, the fatigue load of OWTs may mostly be obtained by standards, mainly including the IEC 61400-1 standard and the Germanischer Lloyd (GL) guideline [158], numerical simulation, and theoretical calculation. Considering short-term fluctuations resulting from the turbulence, Repetto proposed the long-term Monte Carlo simulation method of the bending moment, which is related to the mean wind speed. The rainflow counting algorithm is the common method to be applied in generating different time series of stress with time length ranging between 10 min and three days [159]. Apart from the wind excitations, the wave loads also have an obvious and important influence on the OWT, especially for the bottom-supported structure. A research on fatigue loads was processed based on the nonlinear wave models with consideration for different mean wind speeds and turbulence intensities. The results indicate that the hydrodynamic and aerodynamic loads mainly acting on OWTs may play a different degree of the role in the structural fatigue analysis under standstill and operational conditions [160].

The blades of the OWTs are very sensitive to subtle damage and fatigue loads because of the structural properties of their composite materials. The regulations, including ICE and GL, and numerical simulation methods can be directly used to achieve the blade design and fatigue assessment [161,162]. The fatigue life of the OWT blades can also be estimated by using the well-known S-N linear damage theory, the service load spectrum, and the Spera's empirical equations. Additionally, the fatigue behaviors in response to the vibration at different frequencies and the operational life prediction of wind turbine blades were studied using a numerical method. It also provides a way to compare the material properties and find out the optimum material body [163]. Furthermore, many full-scale experiments on OWT blades have been widely implemented to obtain the dynamic performance, evaluate fatigue life, and even develop smart fatigue load control methods [164] before they are applied in offshore wind farms. The numerical simulations are always used to verify the reliability of test results [165] or present a novel method to improve the accuracy and efficiency of experiments [166]. Recently, lots of new methods and models on fatigue life prediction and assessment have been discussed. Yun aimed to develop a fatigue life prediction method and to identify the effect on the fatigue life of wind turbine blades resulting from the mean wind speed distribution, which can be obtained by the combination of the von Karman isotropic turbulence model and the Weibull distribution [167]. The fatigue stress spectra were created by applying a stress tensor, and the fatigue life could be predicted based on the P–S–N curve obtained from the constant amplitude fatigue tests and cumulative damage rule to the fatigue stress spectra based on the rainflow cycle counting. Caous proposed a progressive damage model by the ply scale to overcome the limitations of fatigue design optimization on wind turbine blades. The new model was also compared with the normative approach for the fatigue assessment and demonstrated its advantage in providing useful information to understand damage propagation [168].

The tower and foundation structures of OWTs are also subject to continuous external excitations and face the risk of fatigue failure. On one hand, fatigue damage may easily occur and propagate in the weak positions or connection parts of steel towers and foundations induced by the long-term excitations because of the nonideal stress distribution or poor material properties. On the other hand, the harsh ocean environment may lead to possible dangerous incidents, especially for the foundations, which are always submerged in seawater, leading to structural component corrosion or the decrease of material strength. Theoretical analysis and numerical simulation are common and important methods in dealing with the fatigue assessment of OWTs. Yeter carried out the fatigue damage assessment on a fixed OWT support structure based on finite element analysis and the combined wave- and wind-induced excitations [169,170]. A wave scatter diagram of the North Atlantic, the rainflow cycle counting method, and S–N fatigue damage approach were all applied in the research in order to account for the environmental effects, count the total number of cycles, and estimate fatigue damage, respectively. Kelma used the peak over threshold method to complete the fatigue analysis and find the probability distribution of the very high stress ranges on the tubular joints of a jacket substructure [171]. It was indicated that the number of the very high stress ranges and scattering for different time series has a significant influence on the resulting fatigue damage based on the application of the maximum-likelihood estimation method. Kvittem studied the discretization of the joint wind and wave distribution including the necessary simulation duration, number of random realizations, and bin sizes in order to achieve the long-term time-domain analysis of the nominal stress [172]. It was completed for the fatigue assessment of the tower and platform members of a three-column semisubmersible structure. An analytical gradient-based method was proposed to solve the problem of the design optimization of OWT structures in an effective and efficient way [173]. The researches on UpWind jacket substructures showed that the design sensitivities of the objective and constraint functions were discussed subjected to size, eigenfrequency, extreme load, and fatigue load constraints while the optimization procedure is performed in the time domain. The influence of changes in soil parameters on the fatigue lifetime of OWTs with a monopile structure has been studied in loose sand. It is explained that changes in soil parameters and soil-pile interaction should be taken into account in the fatigue damage calculations of OWTs for more precise lifetime estimation [174].

Field measurement provides another effective means for the fatigue analysis of OWTs. The strain sensors are always installed around the tower and connection part of the foundation to collect the response reflecting structural dynamic characteristics. Benedetti firstly used the measured data from the tower bottom of a GAIA wind turbine to detect the tracks, and then investigated the possible strategies for residual fatigue life assessment and operational management to determine the number of sensors in turn [175]. The material strength characteristics obtained from fracture mechanics experiments can be used to estimate the critical crack size based on fracture toughness tests, elastoplastic finite element analyses, and loading spectra under extreme wind conditions, and the residual life before the structural collapse. A measurement on a fully instrumented 3.6 MW OWT was used for the estimation of the side-side fatigue loads at the tower bottom considering wind-wave misalignment [176]. The numerical model was also set up to simulate the effect of damping on the side-side fatigue based on a turbulent wind field, irregular waves, and flexible soil, and the sensitivity of the side-side fatigue to the wind-wave misalignment and different values of additional offshore damping in the system was proposed. A new fatigue monitoring strategy, which was proposed by the OWI-lab, focused on how environmental and operational conditions will ultimately affect the fatigue life of OWTs based on measured strain data [177]. It is expected to use the observed relations to build a system which will allow the performing of farm-wide fatigue assessment. Simultaneously, another research area of the OWI-lab mainly aims to discuss how the load measurements can be translated into the fatigue assessment of OWTs under operational conditions [178]. The fatigue progression can be observed by calculating the damage equivalent loads and analyzed against turbulence and site conditions.

5. Reliability Analysis and Safety Evaluation

The feature information extraction and identification of OWTs ultimately serve for the structural reliability analysis and safety evaluation. Reliability analysis aims at quantifying the probability of structural failure and seeking suitable methods to promote the safe operation of the OWT system and enhance reliability management. Safety evaluation is considered as an effective process to identify and analyze failure risks, usually based on measured data, and determine safety strategies and precautions for offshore wind farms [179]. CMS and SCADA systems are common tools to achieve the structural reliability analysis based on the measured data from operational wind turbines [180,181]. However, in recent years, many kinds of novel studies have been completed for the reliability analysis and safety evaluation of OWTs in order to improve the accuracy and feasibility. Considering random material strength, material spatial correlation, progressive material failure, and system reliability effects as main effect factors, a multiaxial probabilistic load model was used to propose a methodology for the structural reliability analysis of wind turbine blades [182]. The data collected from the Windstats survey,

which have characteristics common to practical reliability surveys, was used by Tavner to analyze the reliability of wind turbine components [183]. It is also explained that the wind turbine reliability can be predicted by using grouped survey data and that the turbine design, turbine configuration, time, weather, and possibly maintenance can affect the extracted results. Thereafter, Guo proposed a three-parameter Weibull failure rate function, which has higher accuracy on the reliability growth of wind turbines, to meet the needs of a more general mathematical model and algorithms for wind turbines [184]. The new method will be applicable to the lifetime test of the components and helpful in the understanding of the reliability growth of wind energy systems. Yao set up a finite element model of the wind turbine tower and analyzed the stress distribution induced by wind excitations. The fatigue loads, wind speed distribution, and mean time to failure (MTTF) of towers were calculated with a quantitative reliability theory to implement the reliability analysis of wind turbine towers [185]. The limit state function (LSF) defined by using the structural dynamic response at the mud-line and the dynamic response expressed as the static response multiplied by the peak response factor (PRF) were both considered in the performed reliability analysis of an OWT with a jacket foundation under extreme ocean environmental loads [186]. It is indicated that the reliability index can be found using the first order reliability method (FORM). Furthermore, the impact of turbulence and wave loads, obtained from the full joint probability distribution of wind speed, Monte Carlo (MC) simulations, and IEC standards, on the fatigue reliability of the pile foundations for a 5 MW OWT was investigated [187]. The study results aimed to quantify the influence of environmental models on monopile reliability based on the estimated probability of failure. Zhang provided the explicit internal relation of systems and the preconditions of failure mode analysis in order to propose the floating wind power equipment system based on its structure and function [188]. Dynamic fault tree analysis on floating wind turbines was conducted to discuss sequentially dependent failures and redundancy failures with a search on the failure rates of relevant offshore structures according to previous studies, databases, and reports.

To achieve the structural safety evaluation, two strategically located bidirectional accelerometers were installed on the towers of four OWTs by Gomez to establish a monitoring system and correlate frequency measurements with the overall structural performance of the monopile foundations. The operational modal analysis and system identification techniques were used to obtain frequencies, which were correlated to specific structural performance limit states, including the resonance between the tower and turbine rotor, lack of foundation stability, and yielding of the foundation material, based on the acceleration responses and calibrated computer models [189]. Based on a risk assessment for wind farms during the operation condition, Garcia improved the proactive safety standards and developed a systematic pattern which allows the employers to better handle an emergency event [190]. An occupational risk-scoring method was also proposed for the production stage of wind turbines and all processes [191]. Dong proposed an integral operational modal identification method of the OWT in the range of full power based on traditional and modified SSI techniques and illustrated the modal identification results and the relationship between modal parameters and environmental/operational factors [107,192]. Additionally, the modified SSI technique considering harmonic influence was also used to achieve the structural health assessment of the wind turbine structure by analyzing the relationship between identified modal frequencies and harmonics.

6. Intelligent Operation and Maintenance

After the reliability analysis and safety evaluation of OWTs, the tasks on intelligent operational and maintenance (IO&M) should be implemented in a timely manner based on the condition monitoring and existing problems at offshore wind farms. Generally speaking, operational and maintenance (O&M) costs can account for 10%–20% of the total costs of energy for a wind energy project [193]. The O&M of offshore wind power aims to reduce the costs and increase the power generation of wind turbines and customer revenue throughout the life cycle. Optimal operational and maintenance strategies can be used to aid in improving the reliability and the availability of wind turbines and making them more competitive. The most obvious difference between the O&M of offshore wind power

and onshore wind power can be considered to be the poor accessibility, which makes the O&M of OWTs more difficult and increases the cost due to taking into account many problems such as the distance, weather and sea conditions, unit failure rate, maintenance behavior, power generation capacity, and O&M economy. Hence, more novel techniques for improving maintainability and intelligent operation should be explored and evaluated from both structural safety and benefit-to-cost standpoints.

The operational and maintenance strategy of OWTs can usually be implemented by combining preventive and corrective maintenance. Preventive maintenance is the maintenance carried out before failures occur; on the contrary, corrective maintenance will be carried out after failures occur [194]. Furthermore, preventive maintenance includes scheduled and condition-based maintenance (CBM), which can be used to reduce the operation and maintenance costs of wind power systems. The application of CMSs makes the CBM a good option to reduce the cost related to maintenance [195,196]. Two failure probability thresholds at the wind turbine level were used to define an optimal CBM method and new maintenance policy. The failure probability values at the components and turbine levels can be calculated with the optimal CBM decisions based on condition monitoring and prognostics information [197]. Additionally, reliability-centered maintenance (RCM) can be considered as a systematic method to maintain the balance between preventive and corrective maintenance [194]. Fischer studied the failure frequencies and consequences of critical subsystems in wind turbines, revealed functional failures and underlying causes, and proposed remedial measures in order to prevent both failure and secondary damage. It is used to provide the development of quantitative models with maintenance strategy selection and optimization [198].

In order to improve the effectiveness and efficiency of the OWT maintenance, many pieces of research on IO&M have been implemented. The impacts of wind turbine components' maintenance on downtime was established by using the failure rates, the downtime information, and failure risk based on an improved six-state Markov model [199]. Taking advantage of operation and maintenance data from different sources, a maintenance management framework of the wind turbine was proposed to combine the benefits of age-based and condition-based maintenance scheduling. The problem that the traditional models only provide either an age-based or a condition-based preventive maintenance schedule can be solved using the proposed framework. A modified mathematical model called preventive maintenance scheduling problem with interval costs (PMSPIC) was presented for maintenance optimization, considering both age-based and condition-based failure rate models [200]. IO&M has a more important influence on the structural safety and reliability of OWTs. However, more advanced development of techniques and systems should be achieved in the future. On one hand, these existing techniques are not yet ready to be used and urgently need to be applied and proven in practice in order to allow their large-scale application in OWTs [201]. On the other hand, with the distance farther away from the mainland, it will be a significant act to establish the OWT maintenance information network and the remote IO&M systems to control and manage the offshore wind farms [15].

7. Discussion

The offshore wind resource has great potential in substituting fossil energy and satisfying the necessary energy need for the development of human society. However, with the rapid development of the offshore wind power industry, the problems of structural safety and reliability obtain more attention and may pose obstacles in exploring wind power in the deep ocean. Therefore, the problems that must still be overcome and the future development of abovementioned techniques for OWTs may be discussed as follows:

(1) How can the measured data be collected and transmitted more effectively? Data resources are the research foundation for the online health monitoring and structural safety evaluation of the OWTs. Considering big data theory, establishing a standard database based on a large amount of operational data is of great significance to the innovation of structural health evaluation methods and the grasp of the catastrophe evolution mechanism of the OWTs. The establishment of a database may consist of data acquisition, data storage, and data transmission. Some research is needed to assess the potential of new measurement devices, such as Lidar and wireless sensors [202]. The reliability assessment mechanism and quality evaluation criteria should be adopted to ensure the integrity, accuracy, and timeliness of the measured data. Simultaneously, the future development of offshore wind power will involve moving even further away from the mainland and into deeper waters [203]. There are still many technological challenges in the transmission and integration of measured data further away from the shore. The conventional transmission method based on seabed optical fiber should also be modified to meet the requirement of the real-time transmission of massive monitoring data obtained from different sensors in order to improve the efficiency of the online monitoring and safety evaluation of OWTs.

- (2) How can the feature information on structural safety be obtained more accurately? It is still difficult for engineers to directly measure the external excitations or accurately simulate environmental loads only based on empirical formulas and numerical tools. Simultaneously, due to the continuously rotating blades of OWTs under the operational conditions, structural feature information reflected in measured data may be obviously affected and even be submerged in harmonic excitation interference. Without the clear excitation characteristics and structural responses data, it will pose difficulties in obtaining the accurate feature information, such as modal parameters and damage. On one hand, the further studies may mainly focus on sensor optimization distribution and large area sensing techniques to collect more accurate detail about the structural health or working status [204]. On the other hand, more effective methods and algorithms should be innovated and improved to achieve excitation measurement and reduce the influence on the accuracy of key information identification resulting from different factors.
- (3) How can the safety indicators be determined and the evaluation system be established more reasonably? The operation abnormality of the OWT can be reflected in the monitoring data. After extracting the feature information from the measured data, it is necessary to explain the influence on the OWT structures resulting from the abnormal operation based on suitable indexes or analysis methods. However, due to the influence of the external environment and harmonic excitations, it is more difficult to directly extract safety effect factors from monitoring data and determine safety-sensitive indicators. In future research, the key indicators which affect the structural operational safety and the links between the information contained in the measured data and indicators need to be developed and established. Furthermore, novel intelligent algorithms on modal parameter identification and statistical pattern recognition need to be studied to realize the intelligent characterization of structural feature information. It is also important to find multiple evaluation indicators with better sensitivity and integrate a health assessment indicator system based on the weight of each evaluation index under the abnormality changes, in order to achieve more comprehensive and reliable health evaluation for the OWTs.
- (4) How can the health monitoring and the safety evaluation system be improved and optimized? The improved techniques cannot only be used in the single components, such as the gearbox, generator, blade, tower, and foundation, but also need to be applied in all portions of the wind turbine as a whole [205,206]. It will be easier to understand the structural dynamic behavior and develop the appropriate algorithms or systems for the health monitoring and the safety evaluation of the OWTs. In addition, more optimization methods may be utilized in systems in order to gain more accurate identification of the different feature information and safety evaluation with multiobjective optimization [207]. With the continuous development of scale and water depth for the offshore wind power industry, the standard database and digital integrated monitoring equipment of the whole offshore wind turbines with multi-integrated evaluation indexes must urgently be established for remote health monitoring systems in the future to promote the exploration of intelligent offshore wind farms.
- (5) How can the intelligent operation and maintenance of offshore wind farms be achieved more effectively and economically? The current operation and maintenance of OWT still stays at the

stage of descriptive analysis, and post-fault diagnosis in actual projects lack in pre-judgment assessment and real-time measures. However, with the widespread application of emerging IT technologies such as big data and cloud computing, the use of internet technologies to improve the structural operational stability and the efficiency of wind power generation has become a new trend in the offshore wind power industry. These novel techniques can provide the managers and operators with a reasonable tool to transfer from corrective O&M to preventive O&M. Furthermore, the emerging IT technologies also can be applied in IO&M including data collection and storage, fault detection, real-time weather and power prediction, fault diagnosis and fault pre-judgment in order to reduce the unnecessary economic cost. It is hoped that a fully automated intelligent operation and maintenance system without human intervention can be designed and applied in offshore wind farms in the future.

8. Conclusions

This paper has reviewed the current status of existing health monitoring systems and safety evaluation techniques for OWTs and discussed the key problems and future development. The principal conclusions were drawn as follows:

- (1) SCADA systems and CMS are considered as the two most common types of health monitoring systems of the OWT structure. However, both systems have been attempted to be integrated into each other to significantly improve the efficiency and accuracy of the structural health monitoring of the OWTs. The design and optimization on overall monitoring systems for the whole OWT structure will be the future development trend.
- (2) At present, most research focuses on the novel techniques of feature information extraction and identification. However, the effective indexes and safety evaluation systems which can integrate multiple identification technologies have rarely been proposed and constructed to evaluate the operational safety of OWTs.
- (3) The intelligent operation and maintenance of offshore wind farms, especially in the deep sea, are hoped to be more effective and economic in the future. Internet technologies and information technologies may provide the managers and operators with a reasonable tool to achieve this target.

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